

# Status and Prospects of Supersymmetry Searches at Colliders

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## Abstract

Experiments at particle colliders have reached center of mass energies well above 100 GeV, equivalent to temperatures which existed shortly after the big bang. These experiments, testing the initial conditions of the universe have, with great precision, established the Standard Model of Particle Physics. In contrast, the existence of the Higgs boson and perhaps Supersymmetry remain speculative, as todays searches have failed to find signs of their existence. However, the next generation of high energy collider experiments and especially CERN's 14 TeV LHC, expected to start operation in the year 2005, should lead either to the discovery of the Higgs and Supersymmetry or disprove todays theoretical ideas.

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# 1 Introduction

Experiments at particle colliders have established, with great precision, the validity of today's Standard Model (SM) of particle physics as an accurate description of high energy physics up to mass scales of a few 100 GeV. Among the most precise tests [1], one finds the  $W$  and  $Z$  boson masses and their coupling strength to fermions. Combining all these measurements and staying within the SM one starts being sensitive to the last missing SM particle, the Higgs boson. Furthermore, accurate measurements of the  $Z$  boson width, allowed to determine the number of light neutrino families to be  $2.9835 \pm 0.0083$  and to establish lepton universality with an accuracy well below the 1% level. These precise laboratory measurements lead thus to the requirement that a more complete model has to include today's SM as a low energy approximation. It is often said that physics beyond the SM is required because some fundamental questions are not addressed by the SM. These problems are related to the “unnatural” mass splitting between the known fundamental fermions with neutrino masses close to 0 eV and  $\approx 175 \cdot 10^9$  eV for the top quark and the so called hierarchy problem or fine tuning problem of the Standard Model. The hierarchy problem originates from theoretical ideas to extrapolate today's knowledge at mass scales of a few 100 GeV to energy scales of about  $10^{15}$  GeV and more. A purely theoretical approach to this extrapolation has lead theorists to Supersymmetry and the so-called “Minimal Supersymmetric Standard Model” (MSSM) [2], which could solve some of these conceptual problems by introducing super-symmetric partners to every known boson and fermion and at least an additional Higgs multiplett. As these SUSY particles should have been produced abundantly shortly after the Big Bang, Supersymmetry with R-parity conservation offers a lightest stable super symmetric particle as the “cold dark matter” candidate.

Despite the variety of SUSY models with largely unconstrained masses of SUSY particles and the absence of any indications for Supersymmetry, searches for Supersymmetry at existing and sensitivity estimates of future collider experiments became an important aspect of high energy physics.

This report is structured as follows: it starts with an overview of experimentation at high energy colliders, which includes some recent experimental highlights, we discuss basic concepts of Supersymmetry and the applied search strategies. We then describe a few examples of experiments with negative results at LEP II and the TEVATRON and give an outlook to future perspectives at the LHC.

## 2 Experimentation and Experiments at high Energy Colliders

The high energy frontier of particle colliders are currently covered by the  $e^+e^-$  collider LEP at CERN and the proton–antiproton collider TEVATRON at FER-MILAB. In contrast to  $e^+e^-$  colliders which investigate nature directly at the available center-of-mass energy  $\sqrt{s}$ , proton colliders study of quark and gluon collisions over a wide  $\sqrt{s_{eff}}$  range. The maximal effective  $\sqrt{s_{eff}}$  is however, depending on the available luminosity, about a factor of  $\approx 4$ –6 smaller than the nominal  $\sqrt{s}$  of hadron–hadron collisions.

The LEP collider is currently running at center-of-mass energies,  $\sqrt{s}$ , of 196 GeV and will soon reach  $\sqrt{s} \approx 200$  GeV. The TEVATRON experiments CDF and D0 have collected data corresponding to a luminosity of about  $100 \text{ pb}^{-1}$  per experiment at center-of-mass energies of 1.8 TeV. The upgraded TEVATRON with its improved experiments is expected to restart running in the year 2000 at 2 TeV center-of-mass energies and should provide luminosity of  $1$ – $2 \text{ fb}^{-1}$  per year and experiment. Around the year 2005 the LHC, CERN’s large hadron collider, is expected to come into operation. The LHC is a proton–proton collider with 14 TeV center-of-mass energies and high luminosity. The LHC will allow to increase the sensitivity to new physics well into the TeV mass range.

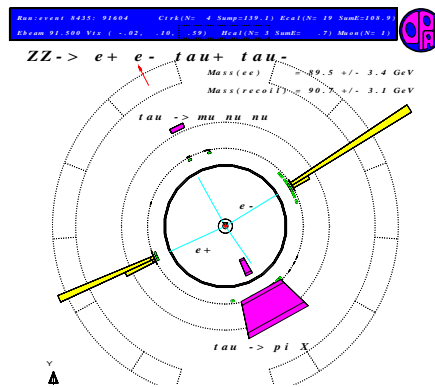


Figure 1: Example of the reaction  $e^+e^- \rightarrow Z^0Z^0 \rightarrow e^+e^-\tau^+\tau^-$  from OPAL at LEP [3]. The mass of the  $e^+e^-$  pair is accurately measured. The mass of the  $\tau\tau$  system is determined indirectly using the recoil mass, estimated from the known  $\sqrt{s}$  and requiring energy and momentum conservation.

Modern Collider experiments have essentially a cylindrical structure with an outer radius of 5–7 m and a length between 10–25 m. The onion like structure of these experiments consists of:

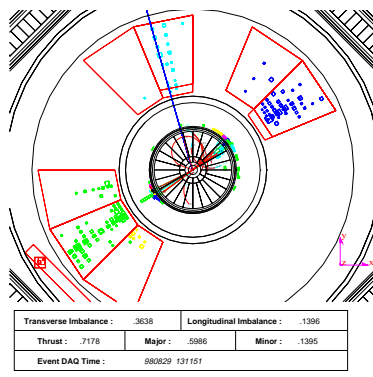


Figure 2: Example of the reaction  $e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}\mu^-\nu$  from L3 at LEP [4]. One sees an isolated stiff track, identified as a muon and two almost back to back hadron jets assigned to the hadronic  $W$  decay. The measured event indicates further that something invisible, the neutrino, is recoiling against the reconstructed muon.

1. Precision detectors which measure precisely the trajectories of charged particles. These detectors are embedded in a magnetic field with a z-axis along the beam direction, which allows to measure the momentum of charged particles.
2. electromagnetic and hadron calorimeters which measure accurately the impact position and the energy electrons, photons and charged or neutral hadrons and,
3. muon detection systems surround the calorimeters and hadron absorbtion length, which measure the position and direction of muons.

While today's collider experiments are constructed and operated by international collaborations of up to 500 physicists one expects that tomorrow's LHC experiments will unite nearly 2000 physicists.

Depending only slightly on the main aim of the experiments, the detectors allow to measure the energy and momentum of long lived charged ( $\pi^\pm$ ,  $K^\pm$ ,  $p$ ,  $\bar{p}$ ,  $e^\pm$  and  $\mu^\pm$ ) as well as the neutral particles  $\gamma$ ,  $K^0$  and  $n$ ,  $\bar{n}$ . These individual particles can then be combined to search for mass peaks of short lived particles,  $\tau$  decay products and bunches of hadrons identified as jets. These jets can be separated using their characteristic lifetime and kinematics into light quark (u,d, and s) or gluon jets, c(harm) and b(eauty) flavoured jets. Furthermore, modern experiments have achieved essentially a  $4\pi$  angular coverage for the various individual energy and momentum measurements, which allows the determination of the missing energy and momentum due to “invisible” neutrinos or neutrino

like objects. Examples of a few interesting events, produced at LEP II and the TEVATRON, are shown in Figures 1–4. These events indicate how the original physics process can be reconstructed from the detectable particles.

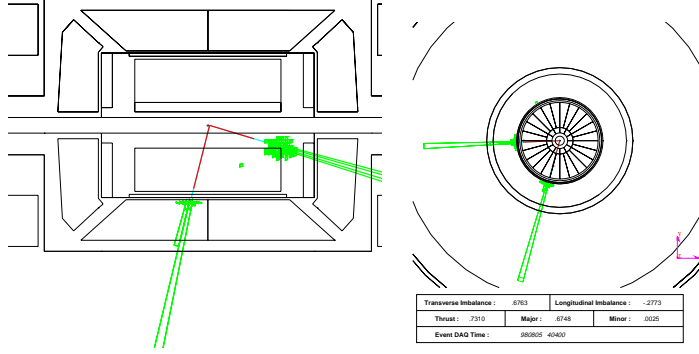


Figure 3: Example from L3 at LEP [4] of the reaction  $e^+e^- \rightarrow W^+W^- \rightarrow e^+\nu e^-\nu$  in a plane including the beam axis and in the plane transverse to the beam. The observed event kinematics indicates clearly that “something” must escape undetected.

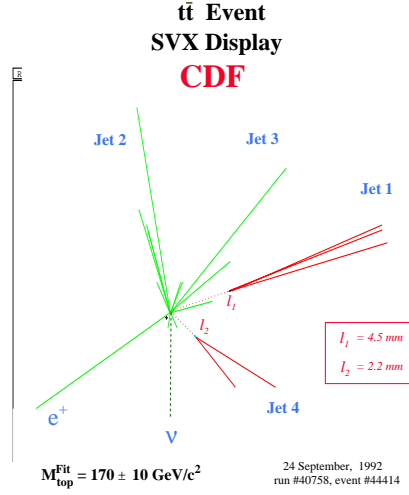


Figure 4: Example of the reaction  $p\bar{p} \rightarrow t\bar{t} \rightarrow e^+\nu b q \bar{q} b$  as seen at the TEVATRON with the CDF detector [5]. Reconstructed charged particle trajectories are shown in an enlarged view of the interaction region. Two separated vertices, assigned to the decay products of b-jets, are visible.

## 2.1 Highlights from Collider Experiments

Despite the non observation of physics beyond the SM, recent experiments at particle colliders gave a large variety of impressive results. Especially remarkable are the measurements of the  $Z$  boson parameters with the resulting number of light neutrino families being  $2.9835 \pm 0.0083$ , the discovery of the top quark at the TEVATRON, the measured cross section of the reaction  $e^+e^- \rightarrow WW$  at LEP II and the observed energy dependence of the strong coupling constant  $\alpha_s$ . Some experimental results and the corresponding theoretical expectations are shown in Figures 5–7.

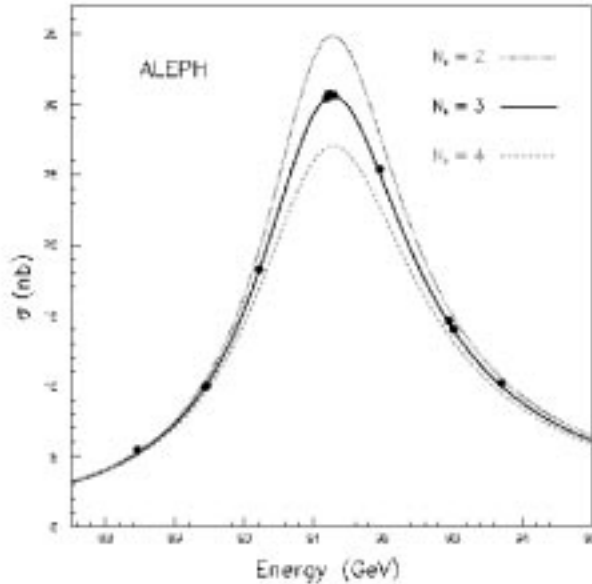


Figure 5: Measured  $Z$  boson cross section for different  $e^+e^-$  center-of-mass energies (from ALEPH) and the theoretical curves assuming 2,3 and 4 light neutrinos [6].

Combining the results of the large variety of collider measurements, one is forced to accept that the SM is at least an excellent approximation of nature. Furthermore, one starts, as shown in Figure 8, to have some indirect constraints on the Higgs boson mass. These indirect constraints are from the combination of the different measurements of electroweak observables, like the various asymmetry

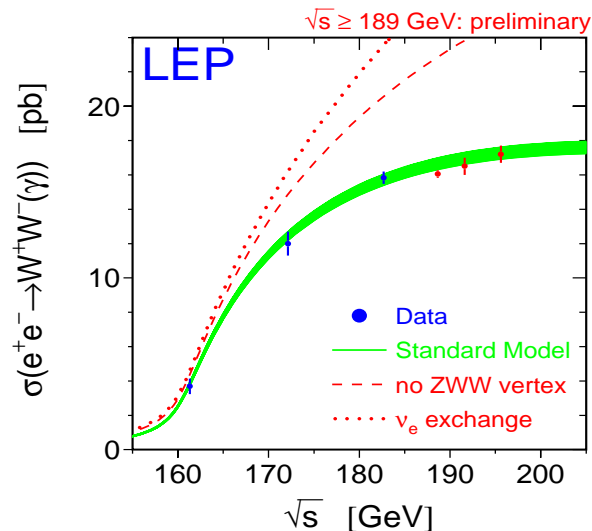


Figure 6: Combination of the measured cross sections for the reaction  $e^+e^- \rightarrow W^+W^-(\gamma)$  from the four LEP experiments (ALEPH, DELPHI, L3 and OPAL) together with the SM expectation and some excluded alternatives [1].

measurements in  $Z$  decays and the masses of the  $W^\pm$  and the top quark. The accuracy of this procedure is however limited as there is only a soft logarithmic Higgs mass dependence. Nevertheless, assuming that the Higgs mass is the only unknown SM parameter, a fit to all precision data constrains the Higgs mass to  $92^{+78}_{-45}$  GeV and with a confidence level of 95% c.l. to less than about 245 GeV [1]. This result agrees with Higgs mass estimates of  $\approx 160 \pm 20$  GeV [8], which assume the validity of the SM up to very large mass scales like the Planck scale. It agrees also with expectations from Supersymmetry with the minimal Higgs sector where the lightest Higgs must have a mass of less than  $\approx 130$  GeV.

The precise measurements of the energy dependence of the strong, the electromagnetic and the weak coupling parameters indicate comparable couplings at energies close to  $10^{15}$  GeV. However, the expectation from the simplest Grand-Unification theories of a perfect matching is now excluded. It might however be achieved if some new physics, like Supersymmetry, exists at nearby mass scales. Another indication of physics beyond today's SM comes from the observed “unnatural” large mass splitting between the otherwise identical fermion families which cover at least 11 orders of magnitude and the “large” number of free parameters within the SM and the exclusion of gravity.

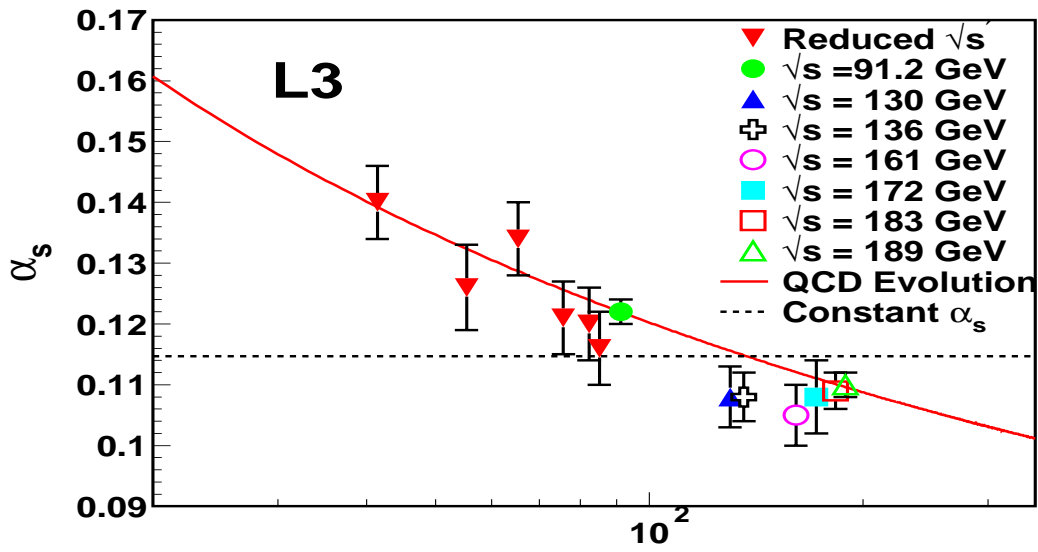


Figure 7: An example of the measured and expected energy dependence of  $\alpha_s$  from L3 at LEP [7].

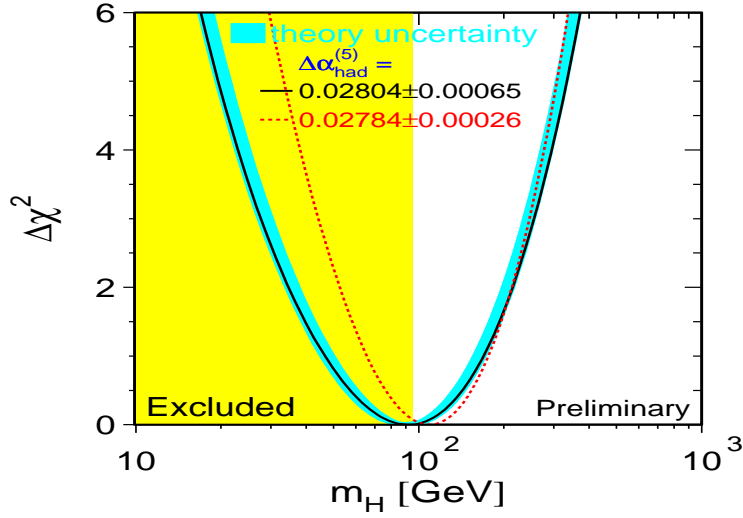


Figure 8:  $\Delta\chi^2$  result of a SM fit to all electroweak observables assuming to have the Higgs mass as the only remaining free parameter [1]. The 95% c.l. SM Higgs mass upper limit is obtained from a  $\chi^2$  variation of 4 with respect to the minimum which corresponds to a value of 22 for 15 degrees of freedom.



### 3 Beyond the Standard Model of Particle Physics: Supersymmetry, SUSY Models and SUSY Signatures

Among the possible extensions of the Standard Model the Minimal Supersymmetric Standard Model (MSSM) [2] is usually considered to give the most serious theoretical frame. The attractive features of this approach are:

- It is quite close to the existing Standard Model.
- It explains the so called hierarchy problem of the Standard Model.
- It allows to calculate.
- Predicts many new particles and thus “Nobel Prizes” for the masses.

An example for the small difference between the SM and the MSSM in terms of electroweak observables is shown in Figure 9 [9], which compares the measurements of the  $W$ -boson and the top-quark masses with predictions of the SM and the MSSM.

Unfortunately today's data,  $M_W = 80.394 \pm 0.042$  GeV and  $M_{top} = 174 \pm 5$  GeV [1], favor an area which is perfectly consistent with both models. Similar conclusion can be drawn from other comparisons of today's precision measurements with the SM and the MSSM.

A large number of new heavy particles should exist within the MSSM model. In detail, one expects spin 0 partners, called sleptons and squarks for every quark and lepton and spin 1/2 partners, called gluinos, charginos and neutralinos, for the known spin 1 bosons and for the hypothetical scalar Higgs bosons. Due to identical quantum numbers, some mixing between the different neutralinos and charginos might exist. In addition, at least 5 Higgs bosons ( $h^0, H^0, A^0$  and  $H^\pm$ ) are required. The masses of these Higgs bosons are strongly related. Essentially one needs to know “only” the mass of  $h^0$  and one other Higgs boson or the mass of one Higgs boson and  $\tan\beta$ , the ratio of the Higgs vacuum expectation values.

Experimental searches for Supersymmetry can thus be divided into a) the MSSM Higgs sector and b) the direct SUSY particle search.

The advantages of searches for a Higgs boson are that at least one Higgs boson with a mass smaller than about 130 GeV [10] should exist and that cross sections and decay modes can be calculated accurately as a function of the mass and  $\tan\beta$ . The disadvantage is however that, in order to distinguish between the SM and Supersymmetry, at least two MSSM Higgs bosons need to be discovered.

In contrast to Higgs searches, searches for SUSY particles can look for a variety of SUSY particles and the discovery of one SUSY particle could be a proof of Supersymmetry. Unfortunately the masses of SUSY particles cannot be

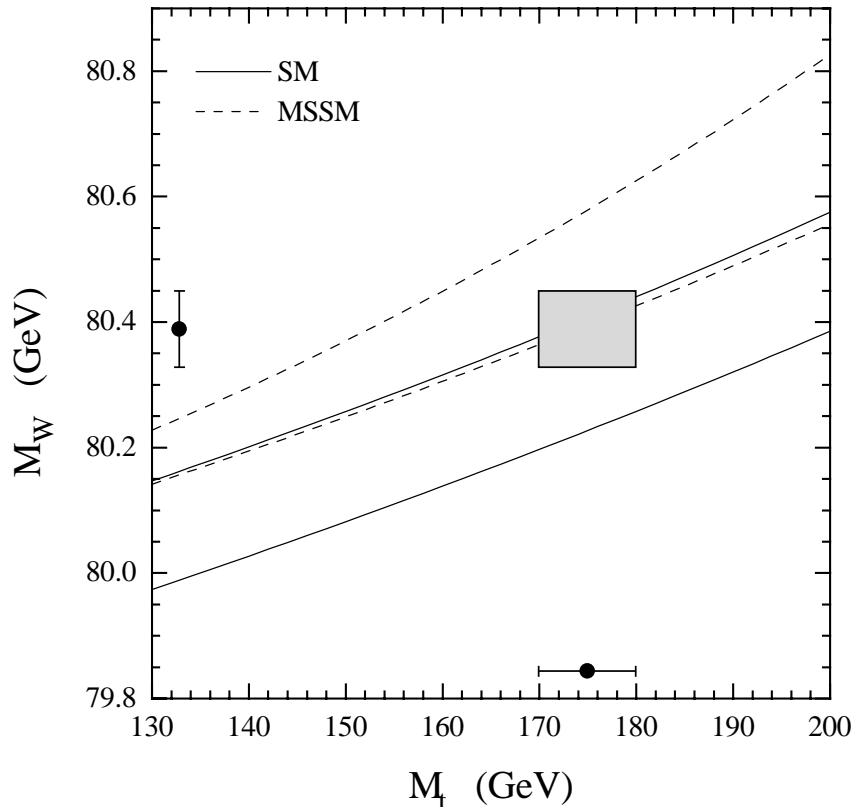


Figure 9: Expected relation between  $M_W$  and  $M_{top}$  in the Standard Model and the MSSM, the bounds are from the non-observation of Higgs or SUSY particles at LEP II [9]. The 1998 experimental area, with  $M_W = 80.39 \pm 0.06$  GeV and  $M_{top} = 174 \pm 5$  GeV is also indicated.

predicted and values far beyond today's and perhaps even tomorrow's center-of-mass energies are possible. Furthermore, having over 100 free SUSY parameters a large variety of SUSY signatures needs to be studied.

As will be discussed in section 4.1, today's negative search results for Higgs particles at LEP II indicate that the mass of the lightest SUSY Higgs must be greater than about 80-90 GeV. The absence of any indication for supersymmetric particles at LEP II and the TEVATRON, discussed below imply mass limits of about 90 GeV for sleptons, 95 GeV for charginos and about 200 GeV for squarks and gluinos [11].

### 3.1 Signatures of SUSY Particles

Essentially all signatures related to the MSSM are based on the consequences of R-parity conservation [12]. R-parity is a multiplicative quantum number like ordinary parity. The R-parity of the known SM particles is 1, while the one for the SUSY partners is  $-1$ . As a consequence, SUSY particles have to be produced in pairs. Unstable SUSY particles decay, either directly or via some cascades, to SM particles and the lightest super symmetric particle, LSP, required by cosmological arguments to be neutral. Such a massive LSP's, should have been abundantly produced after the Big Bang and is currently considered to be “the cold dark matter” candidate.

This LSP, usually assumed to be the lightest neutralino  $\tilde{\chi}_1^0$  has neutrino like interaction cross sections and cannot be observed in collider experiments. Events with a large amount of missing energy and momentum are thus the SUSY signature in collider experiments. Due to neutrinos produced in weak decays of for example  $\tau$  leptons and measurement errors, the missing energy and momentum signature alone are usually not sufficient to identify SUSY particles.

However, SM backgrounds can be strongly reduced if the decay kinematics of heavy particles are exploited. The decay products of heavy particles obtain a relatively large  $p_\perp$  with respect to the momentum vector of the decaying particle and can thus be emitted with large angles. Consequently, the observable decay products of pair produced heavy SUSY particles should thus be seen in non back-to-back events. Due to the detection hole close to the beam line, missing momentum along the beam direction is also be expected for standard physics reactions. SUSY searches concentrate thus on the missing momentum in the plane transverse to the beam direction and require usually some non back-to-back signature in this x-y plane. Essentially all the characteristics of SUSY searches, large missing momentum, energy and the non back-to-back signature are also used to select  $e^+e^- \rightarrow WW \rightarrow \ell^+\nu\ell^-\bar{\nu}$  events at LEP II as visualized in events like the one shown in Figure 3. Due to the relatively large  $W$  mass and cross section, SUSY searches at LEP II and other colliders need to consider especially the potential backgrounds from the SM reaction  $e^+e^- \rightarrow WW$ .

Possible SUSY search examples, which exploit the above signatures are the pair production of sleptons with their subsequent decays,  $e^+e^- \rightarrow \tilde{\ell}^+\tilde{\ell}^-$  and  $\tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$ . Such events would appear as events with a pair of isolated electrons or muons with high  $p_t$  and large missing transverse energy.

Starting from the MSSM, the so called minimal model, one counts more than hundred free parameters. So many unconstrained parameters do not offer a good guidance for experimentalist which prefer to use additional assumptions. The perhaps simplest approach is the MSUGRA (minimal super gravity) model with only five free parameters ( $m_0, m_{1/2}, \tan\beta, A^0$  and  $\mu$ ). Within the MSUGRA model, the masses of SUSY particles are strongly related to the so called universal fermion and scalar masses  $m_{1/2}$  and  $m_0$ . The masses of the spin 1/2 SUSY particles are

directly related to  $m_{1/2}$ . One expects approximately the following mass hierarchy:

- $\tilde{\chi}_1^0 \approx 1/2 m_{1/2}$
- $\tilde{\chi}_2^0 \approx \tilde{\chi}_1^\pm \approx m_{1/2}$
- $\tilde{g}$  (the gluino)  $\approx 3m_{1/2}$

The masses of the spin 0 SUSY particles are related to  $m_0$  and  $m_{1/2}$  and allow, for some mass splitting between the “left” and “right” handed scalar partners of the degenerated left and right handed fermions. One finds the following simplified mass relations:

- $m(\tilde{q})$  (with  $q=u,d,s,c$  and  $b$ )  $\approx \sqrt{m_0^2 + 6m_{1/2}^2}$
- $m(\tilde{\nu}) \approx m(\tilde{\ell}^\pm)$  (left)  $\approx \sqrt{m_0^2 + 0.52m_{1/2}^2}$
- $m(\tilde{\ell}^\pm)$  (right)  $\approx \sqrt{m_0^2 + 0.15m_{1/2}^2}$

The masses of the left and right handed stop quarks ( $\tilde{t}_{\ell,r}$ ) might, depending on other parameters, show a large mass splitting. As a result, the right handed stop quark might be the lightest of all squarks.

Following the above mass relations and using the known SUSY couplings, possible SUSY decays and the related signatures can be defined. Already with the simplest MSUGRA frame one finds a variety of decay chains.

For example the  $\tilde{\chi}_2^0$  could decay to  $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + X$  with  $X$  being:

- $X = \gamma^* Z^* \rightarrow \ell^+ \ell^-$
- $X = h^0 \rightarrow b\bar{b}$
- $X = Z \rightarrow f\bar{f}$

Other possible  $\tilde{\chi}_2^0$  decay chains are  $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^{\pm(*)} + \ell^\pm \nu$  and  $\tilde{\chi}_1^{\pm(*)} \rightarrow \tilde{\chi}_1^0 \ell^\pm \nu$  or  $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^\pm \ell^\mp$ .

Allowing for higher and higher masses, even more decay channels might open up. It is thus not possible to define all search strategies a priori. Furthermore, possible unconstrained mixing angles between neutralinos, lead to model dependent search strategy for squarks and gluinos.

## 4 Where we did not discover Supersymmetry

### 4.1 The Higgs Search at LEP II and beyond

Experiments at LEP II and  $\sqrt{s} \approx 200$  GeV will have an excellent sensitivity to the SM Higgs with masses of about 100–105 GeV, using the process  $e^+e^- \rightarrow Z^* \rightarrow Zh^0$ . The experimental signatures for this process are given by the combination of the various decay products of a  $Z$  boson and two  $b$ -jets or  $\tau\tau$  final states coming from the decay of the Higgs boson. Furthermore, due to kinematic constraints the mass of the system recoiling against the  $Z$  system can be measured with an accuracy of about  $\pm 2$ –3 GeV and a signal should show up in the recoil mass spectrum. The latest LEP results, obtained using the 1998 data at  $\sqrt{s} = 189$  GeV and a luminosity of  $\approx 180$  pb $^{-1}$ /experiment, do not show any signal. Only OPAL sees a two sigma excess of events with a recoil mass close to the  $Z$  mass as shown in Figure 10 [13]. The observed number of events in the peak region

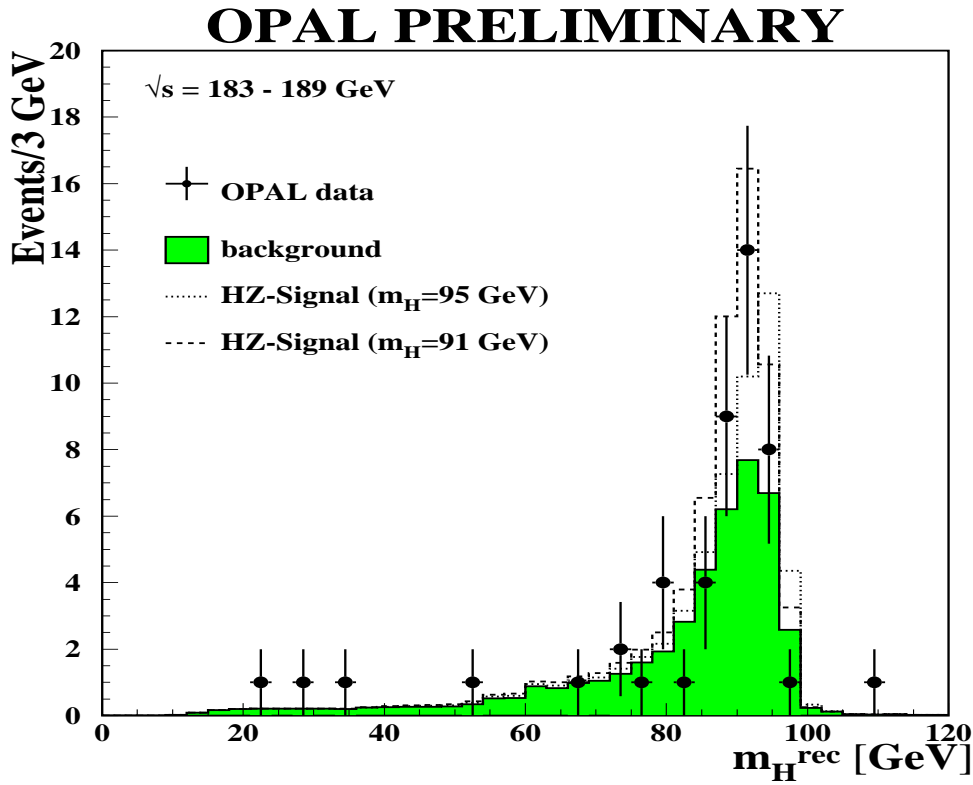


Figure 10: Observed and expected mass distributions from the OPAL Higgs search using the data collected in the years 1997 and 1998 [13].

is 31 compared to a background expectation of  $\approx 22$  events. Unfortunately the

excess is neither confirmed by the new OPAL data collected up to July 1999 [14] nor by the combination of the four LEP experiments and the 1998 data as shown in Figure 11 [15].

For higher values of  $\tan\beta$  the couplings of the  $h^0$  to the weak bosons are reduced proportional to  $\cos\beta$ . However, the reaction  $e^+e^- \rightarrow Z^* \rightarrow h^0 A^0$ , if kinematically allowed, appears to be detectable. This process results in a distinct signature of events with four b-jets. The search for such 4 b-jet events during the future LEP II running will thus give sensitivity to masses of  $M_h, M_A < 90 - 100$  GeV and all  $\tan\beta$  values. The possible final SM Higgs sensitivity from the 1999/2000 data taking at LEP II has been estimated to be about 105 GeV, using a luminosity of about  $4 \times 200 \text{ pb}^{-1}$  at  $\sqrt{s} = 200$  GeV [16]. One finds that this sensitivity translates to a Higgs sensitivity of the MSSM for values of  $\tan\beta$  of about roughly 6–7 (3–4) with no (maximal) mixing using the process  $e^+e^- \rightarrow Z^* \rightarrow Zh^0$ .

Searches for Higgs bosons with masses beyond the expected LEP II sensitivity have probably to wait for the LHC or perhaps even for a future high luminosity high energy linear  $e^+e^-$  collider.

Today's sensitivity studies from both large LHC experiments, ATLAS [18] and CMS [19], indicate an excellent sensitivity to SM Higgs boson up to masses of about 1 TeV. The sensitivity to the Higgs sector of the MSSM scenario appears currently to be somehow restricted. For the lightest Higgs, with a mass below 120–130 GeV, the only established signature is the decay  $h^0 \rightarrow \gamma\gamma$ . For masses of  $M_A$ , greater than 400 GeV the  $h^0$  behaves essentially like the SM Higgs rates and should be discovered a few years after the LHC start. For smaller masses of  $M_A$ , the branching ratio  $h \rightarrow \gamma\gamma$  becomes too small to be observable and 5 standard deviation  $h^0$  signals can only be expected from the combination of the  $h^0 \rightarrow \gamma\gamma$  search with other  $h^0$  decay modes, like  $pp \rightarrow t\bar{t}h^0 \rightarrow b\bar{b}$ ,  $h^0 \rightarrow ZZ^*$  and  $h^0 \rightarrow WW^*$ . The regions where one should see 5 standard deviation MSSM Higgs signals and with integrated luminosity of  $30 \text{ fb}^{-1}$ , about three years after the LHC start and with a “final” luminosity of  $300 \text{ fb}^{-1}$  are indicated in Figures 12a and b, respectively. The expected sensitivity of the LHC experiments to other Higgs bosons of the MSSM are also indicated in Figure 12.

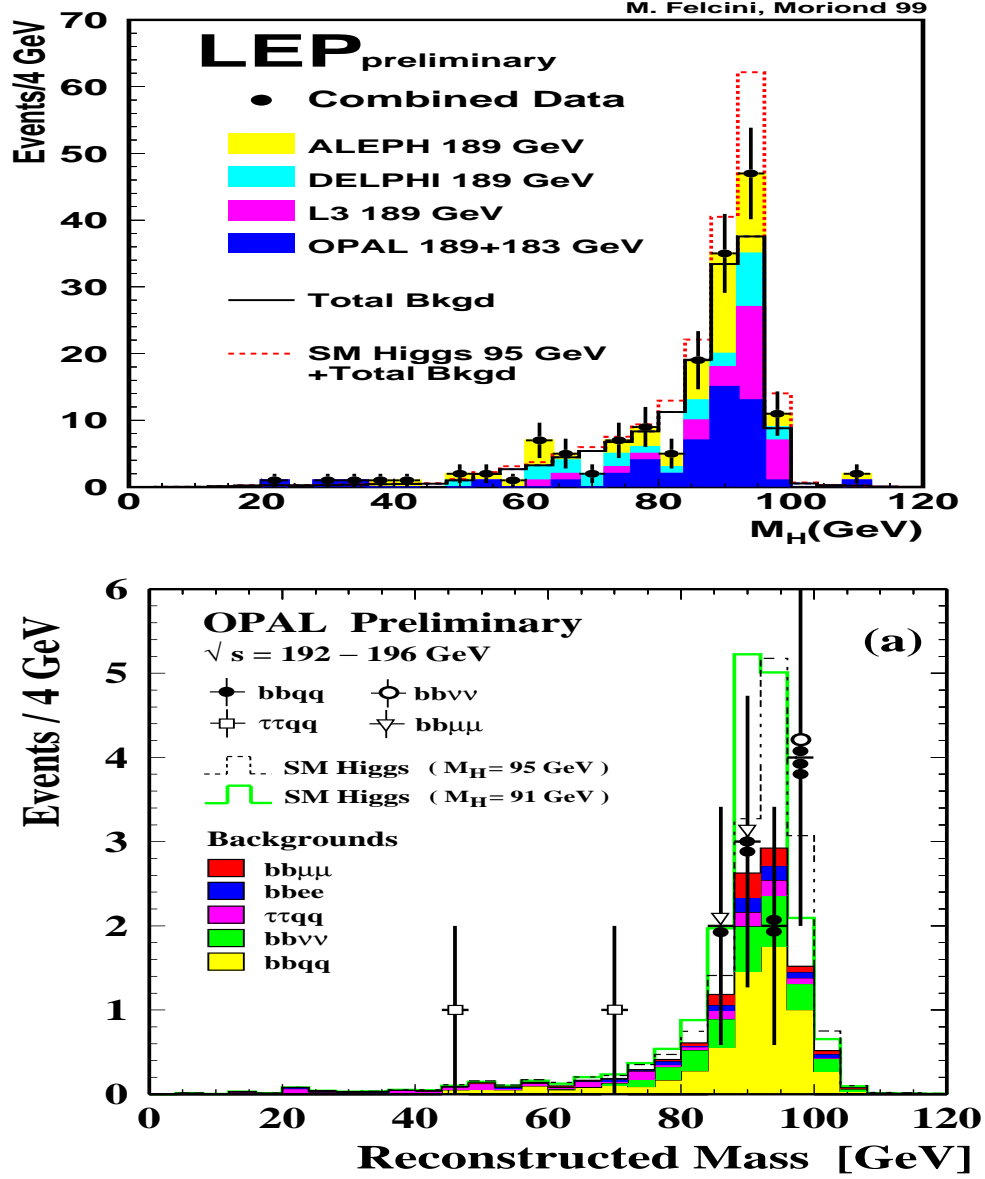


Figure 11: Mass distribution for Higgs candidates from ALEPH, DELPHI, L3 and OPAL in the 1998 data sample [15] and from the preliminary 1999 OPAL data, collected up to July [14]. The expected mass distribution for backgrounds and a SM Higgs with a of 95 GeV are also shown..

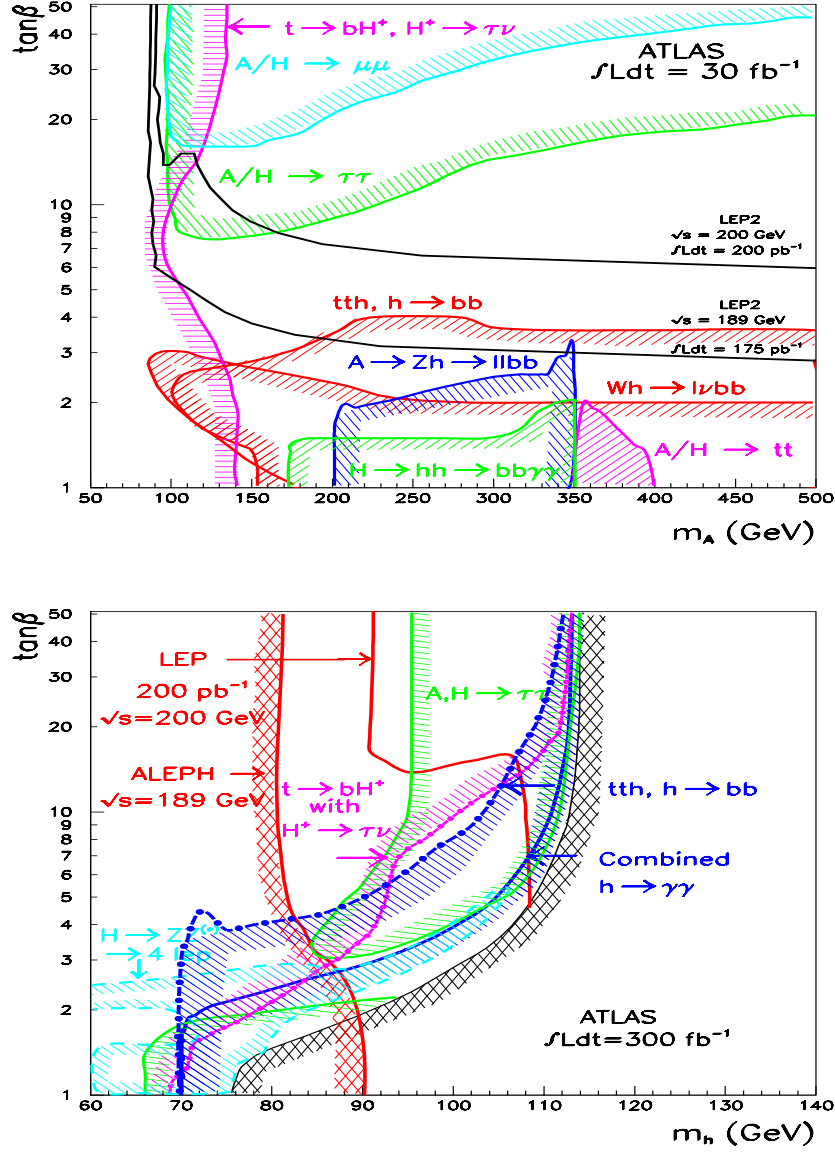


Figure 12: ATLAS [17] 5 sigma significance contour plot for the different MSSM Higgs sector in the  $M_A$  -  $\tan\beta$  plane and for  $30 \text{ fb}^{-1}$ . The lower plot shows the ultimate ATLAS 5 sigma discovery sensitivity for the MSSM with a luminosity of  $300 \text{ fb}^{-1}$  in the  $M_h$  -  $\tan\beta$  plane. Each curve indicates the sensitivity for different Higgs search modes.



## 4.2 Examples of todays direct SUSY Searches

Today's searches cover a wide range of MSSM SUSY models, going from the most “conservative” MSUGRA model to more “radical” assumptions like Gauge mediated models and models with R-parity violation. But so far and despite the large variety of studied signatures, no indication for SUSY like particles has been found at LEP II, at the TEVATRON or at HERA.

To demonstrate the good experimental sensitivity it appears to be useful to discuss the actual outcome of a few SUSY searches at LEP II and the TEVATRON.

The first example is the search for acoplanar lepton pairs events from OPAL at LEP II [20]. The distribution of the lepton energy scaled by the beam energy and the reconstructed scattering angle multiplied by the charge of the most energetic lepton with respect to the incoming electron direction are shown in Figures 13a and b respectively. The data are in agreement with expectations from the dominant  $WW$  backgrounds. The possibility to discriminate potential signal events from the backgrounds using the characteristic charge dependent angular distribution is nicely seen in Figure 13b.

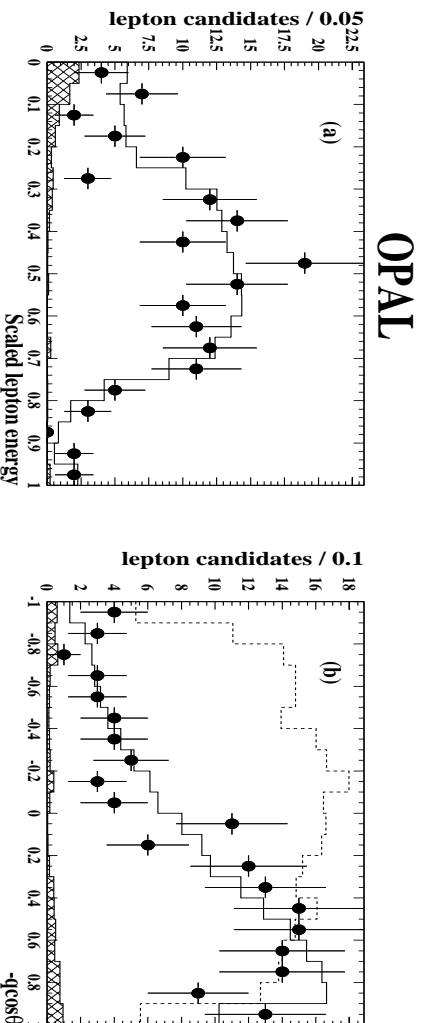


Figure 13: Observed and expected distributions of acoplanar lepton pair events from OPAL [20]. Shown are the scaled lepton energy ( $E_{\ell^\pm}/E_{Beam}$ ) (a) and (b) the reconstructed scattering angle multiplied with the associated charge with respect to the  $e^-$  beam direction.

The second example are results from L3, summarized in Table 1 [21]. The observed number of events in the data are compared with expected backgrounds and optimized searches for sleptons and charginos, with small, medium and large mass differences between the lightest stable SUSY particle and the studied SUSY particle. Not even a two sigma excess is seen. An interpretation of the L3 results, within the MSSM model, is given in Figure 14.

$\sqrt{s} = 189 \text{ GeV}$ data						
	Low $\Delta M$		Medium $\Delta M$		High $\Delta M$	
	$N_{Data}$	$N_{exp}$	$N_{Data}$	$N_{exp}$	$N_{Data}$	$N_{exp}$
$\tilde{e}$	7	6	3	4.8	11	12.4
$\tilde{\mu}$	10	11.5	2	1	8	9.1
$\tilde{\tau}$	4	2.7	3	8.4	9	11.9
$\chi^\pm$	72	66.9	11	10.9	67	76.7
$\chi^0_2$	43	39.3	6	7.78	3	2.45

Table 1: Observed and expected (SM) number of events for slepton, chargino and neutralino searches with L3 at LEP [21].

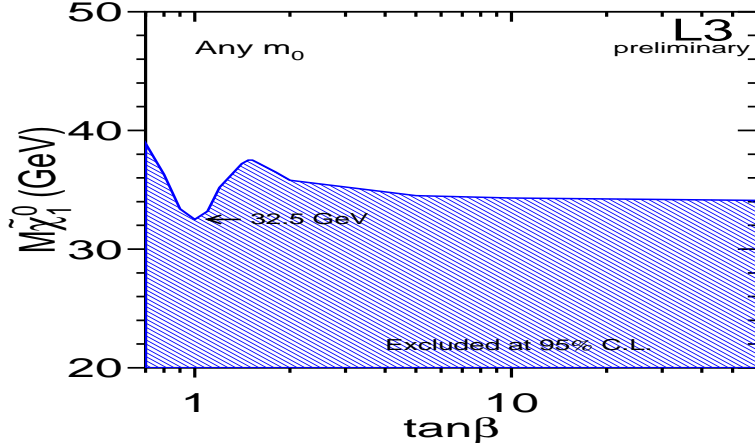


Figure 14: Excluded mass range for  $\tilde{\chi}_1^0$  and  $\tan\beta$  obtained from the combined chargino and neutralino searches in L3 and the data taken at  $\sqrt{s} = 189 \text{ GeV}$  [21].

The third example is related to a search for trilepton events, originating from the reaction  $q_i \bar{q}_j \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$  and leptonic decays of the neutralino and chargino. Such events can be detected from an analysis of events with three isolated high  $p_t$  leptons and large missing transverse energy. The potential of this trilepton signature at hadron colliders like the LHC has been described in several phenomenological studies [22]. It was found, that trilepton events with jets need to be rejected in order to distinguish signal events from SM and other SUSY backgrounds.

After the removal of jet events, the only remaining relevant background comes from leptonic decays of  $WZ$  events. Potential backgrounds from dilepton events like  $W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$  and hadrons misidentified as electrons or muons are usually assumed to be negligible. Depending on the analyzed SUSY mass range,

the background from leptonic decays of  $WZ$  events, in contrast to a potential signal, will show a  $Z^0$  mass peak in the dilepton spectrum. The results of a TEVATRON (CDF) trilepton search [23] are shown in Table 2.

Cut	observed Events	SM Background Expectation	MSSM MC $M(\tilde{\chi}_1^\pm) = M(\tilde{\chi}_2^0) = 70 \text{ GeV}$
Dilepton data	3270488		
Trilepton data	59		
Lepton Isolation	23		
$\Delta R_{\ell\ell} > 0.4$	9		
$\Delta\phi_{\ell\ell} < 170^\circ$	8	$9.6 \pm 1.5$	$6.2 \pm 0.6$
$J/\Psi, \Upsilon, Z$ removal	6	$6.6 \pm 1.1$	$5.5 \pm 0.5$
missing $E_t(miss) > 15$	0	$1.0 \pm 0.2$	$4.5 \pm 0.4$

Table 2: Results from a recent trilepton analysis from CDF with a dataset of  $\approx 100 \text{ pb}^{-1}$  [23]. The number of observed events shows good agreement with various SM background sources.

The last example is related to the famous lonely CDF event, which has large missing transverse energy, 2 high  $p_t$  isolated photons and 2 isolated high  $p_t$  electron candidates [24]. The presence of high  $p_t$  photons does not match MSUGRA expectations but might fit into so called gauge mediated symmetry breaking models, GMSB [25]. This event has motivated many additional, so far negative searches. Particular sensitive searches at LEP II come from the analysis of events with one or more energetic photons and nothing else. Such events can originate essentially only from initial state bremsstrahlung in the reaction  $e^+e^- \rightarrow Z\gamma\gamma$  and the  $Z$  decaying to neutrinos or from the neutralino pair production and subsequent decays to photons and invisible gravitinos. No excess of such events has been seen by any of the LEP experiments. These negative results exclude essentially the SUSY interpretation of the CDF event. Typical results, here from L3, for the recoil mass distribution of single and double  $\gamma$  events and their interpretation in comparison with the area allowed by the CDF event, are shown in Figures 15a-c [26].

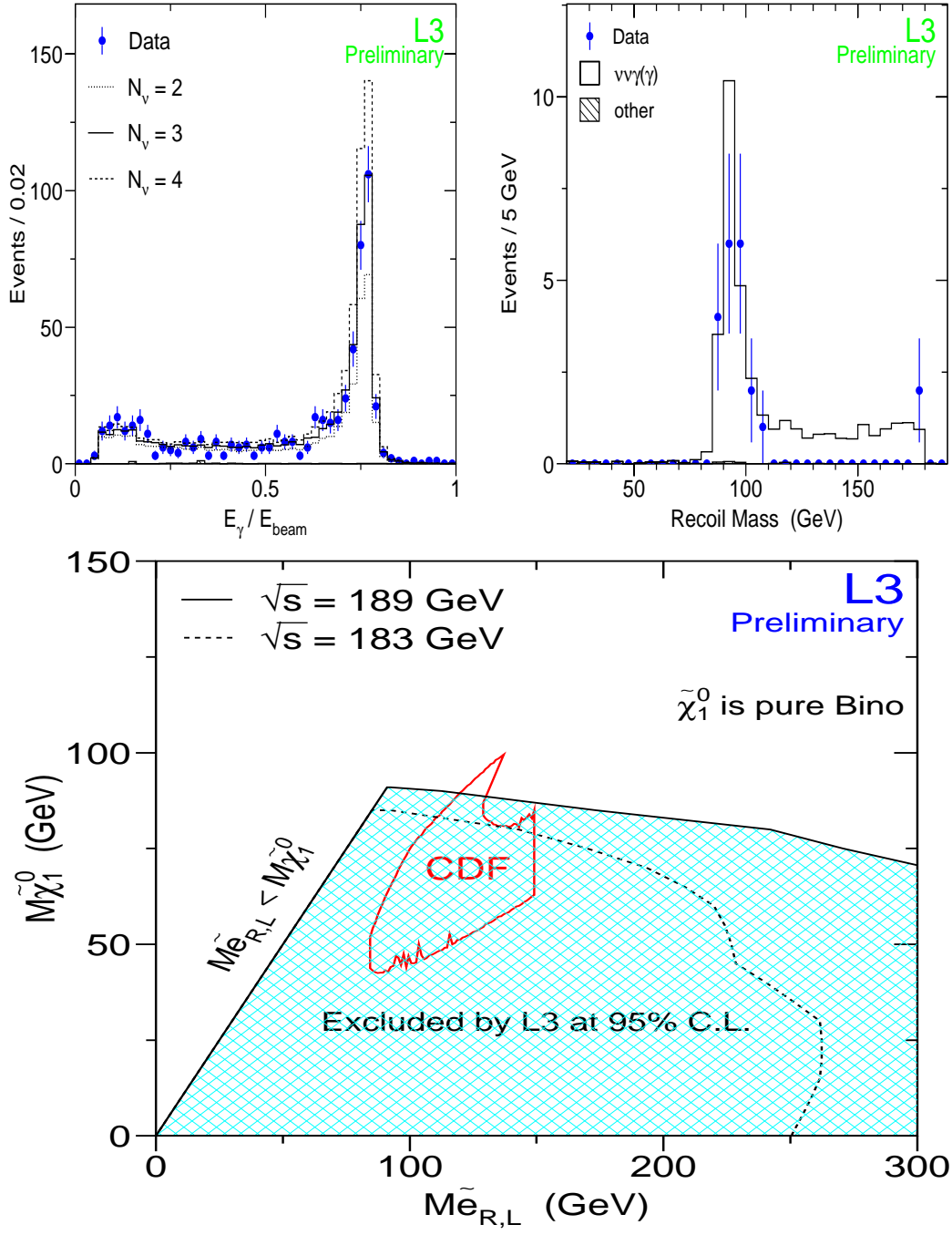


Figure 15: The scaled energy and recoil mass distribution of events which consist of single or double photons as observed and expected by the L3 experiment [26]. The lower plot shows the interpretation of the LEP II data within the assumed model and in comparison with the CDF event.

### 4.3 Where we might discover SUSY particles

The data taking at LEP II will continue during the year 2000, with an expected maximal  $\sqrt{s}$  of  $\approx 200$  GeV. In contrast to the MSSM Higgs search, where a still a sizeable fraction of the parameter space can be covered, the increase in the mass range from  $\approx 90$  GeV to 95 GeV appears to be small compared to possible TeV scale masses of SUSY particles.

The next phase of direct SUSY searches will thus be dominated by hadron colliders. The improved TEVATRON collider is expected to start data taking during the year 2000. The expected yearly luminosity for the so called RUN II should reach a few  $\text{fb}^{-1}$  per experiment. This should allow to discover the reaction  $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$  with SUSY masses up to 130 GeV. Further improvements could come from the third phase of the TEVATRON (RUN III), which could reach chargino masses up to about 210 GeV and integrated luminosities of 20–30  $\text{fb}^{-1}$  [27]. The final test of the MSSM version of Supersymmetry should come from CERN's LHC, currently expected to start operation during the year 2005. LHC experiments are especially sensitive to strongly interacting particles with their huge production cross section. For example, the pair production cross section of squarks and gluinos with a mass of  $\approx 1$  TeV has been estimated to be as large as 1 pb resulting in  $10^4$  produced SUSY events for one “low” luminosity LHC year [28]. Depending on the SUSY model, a large variety of massive squark and gluino decay channels and signatures might exist. A complete search analysis for squarks and gluons at the LHC should consider the various signatures resulting from the following decay channels.

- $\tilde{g} \rightarrow \tilde{q}q$  and perhaps  $\tilde{g} \rightarrow \tilde{t}t$
- $\tilde{q} \rightarrow \tilde{\chi}_1^0 q$  or  $\tilde{q} \rightarrow \tilde{\chi}_2^0 q$  or  $\tilde{q} \rightarrow \tilde{\chi}_1^\pm q$
- $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$  or  $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^0$  or  $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h^0$
- $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \ell^\pm \nu$  or  $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W^\pm$ .

The various decay channels can be separated into at least three distinct event signatures.

- Multi-jets plus missing transverse energy. These events should be “circular” in the plane transverse to the beam.
- Multi-jets plus missing transverse energy plus  $n(=1,2,3,4)$  isolated high  $p_t$  leptons. These leptons originate from cascade decays of charginos and neutralinos.
- Multi-jets plus missing transverse energy plus same charge leptons pairs. Such events can be produced in events of the type  $\tilde{g}\tilde{g} \rightarrow \tilde{u}\tilde{u}\tilde{d}\tilde{d}$  with subsequent decays of the squarks to  $\tilde{u} \rightarrow \tilde{\chi}_1^+ d$  and  $\tilde{d} \rightarrow \tilde{\chi}_1^+ u$  followed by leptonic chargino decays  $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 \ell^+ \nu$ .

It is easy to imagine that the observation and detailed analysis of the different types of squark and gluino signatures might allow to measure some of the many MSSM parameters.

The above signatures have already been investigated with the data from the TEVATRON RUN I. The negative searches gave mass limits for squarks and gluinos up to  $\approx 200$  GeV. The estimated 5-sigma sensitivity for RUN II and RUN III reaches values as high as 350–400 GeV. More details about the considered signal and backgrounds can be found from the TeV2000 studies [27] and the ongoing TEVATRON RUN II workshop [29].

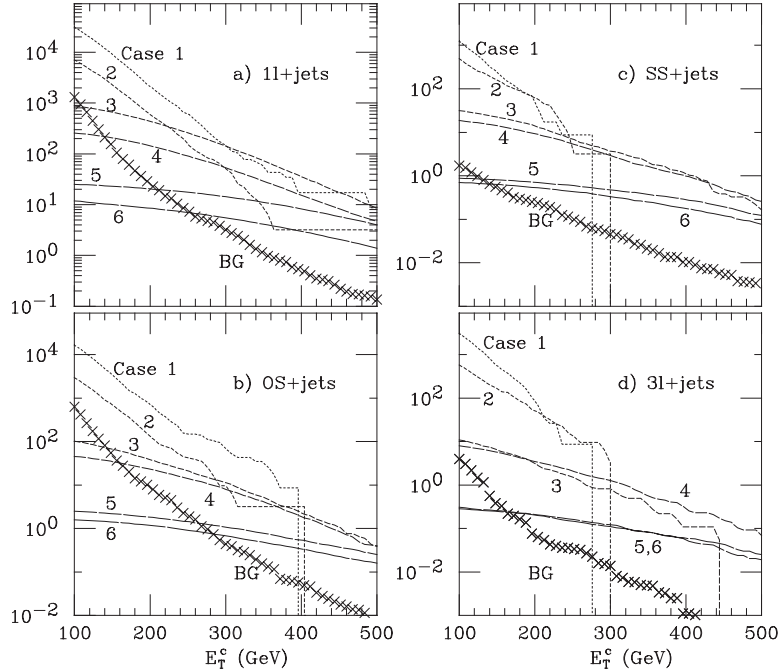


Figure 16: Expected  $E_t^c$  distributions for SUSY signal and background processes at the LHC and realistic experimental cuts for  $\tan \beta = 2$  and  $\mu < 0$  [30]. The different cases are for: (1)  $m_{\tilde{g}} = 290$  GeV and  $m_{\tilde{q}} = 270$  GeV; (2)  $m_{\tilde{g}} = 310$  GeV and  $m_{\tilde{q}} = 460$  GeV; (3)  $m_{\tilde{g}} = 770$  GeV and  $m_{\tilde{q}} = 720$  GeV; (4)  $m_{\tilde{g}} = 830$  GeV and  $m_{\tilde{q}} = 1350$  GeV; (5)  $m_{\tilde{g}} = 1400$  GeV and  $m_{\tilde{q}} = 1300$  GeV; (6)  $m_{\tilde{g}} = 1300$  GeV and  $m_{\tilde{q}} = 2200$  GeV.

A simplified search strategy for squarks and gluinos at the LHC would study jet events with large visible transverse mass and some missing transverse energy. Such events can then be classified according to the number of isolated high  $p_t$

leptons. Once an excess above SM backgrounds is observed for any possible combination of the transverse energy spectra, one would try to explain the observed types of exotic events and their cross section(s) for different SUSY  $\tilde{g}, \tilde{q}$  masses and decay modes and models. An interesting approach to such a multi-parameter analysis uses some simplified selection variables. For example one could use the number of observed jets and leptons and their transverse energy, their mass and the missing transverse energy to separate signal and backgrounds. Such an approach has been used to perform a “complete” systematic study of  $\tilde{g}$  and  $\tilde{q}$  decays [30]. The proposed variable  $E_t^c$  is the value of the smallest of  $E_t(\text{miss})$ ,  $E_t(\text{jet1})$ ,  $E_t(\text{jet2})$ . The events are further separated into the number of isolated leptons. Events with lepton pairs are divided into same sign (charge) pairs (SS) and opposite charged pairs (OS). Signal and background distributions for various squark and gluinos masses, obtained with such an approach are shown in Figure 16. According to this classification the number of expected signal events can be compared with the various SM background processes. The largest and most difficult backgrounds originate mainly from  $W+\text{jet(s)}$ ,  $Z+\text{jet(s)}$  and  $t\bar{t}$  events. Using this approach, very encouraging signal to background ratios, combined with quite large signal cross sections are obtainable for a large range of squark and gluino masses. The simulation results of such studies indicate, as shown in Figure 17, that the LHC experiments are sensitive to squark and gluinos masses up to masses of about 2 TeV,  $m_{\tilde{g}} = 3 \cdot m_{1/2}$ , and a luminosity of  $100 \text{ fb}^{-1}$ .

Figure 17 indicates further, that detailed studies of branching ratios are possible up to squark or gluino masses of about 1.5 TeV, where significant signals can be observed with many different channels. Another consequence of the expected large signal cross sections is the possibility that the “first day” LHC luminosity  $\approx 100 \text{ pb}^{-1}$  should be sufficient to discover squarks and gluinos up to masses of about 600–700 GeV, well beyond even the most optimistic TEVATRON Run III mass range.

#### 4.4 SUSY discovered, what can be studied at the LHC?

Being convinced of the LHC SUSY discovery potential, one certainly wants to know if “the discovery” is consistent with Supersymmetry and if some of the many SUSY parameters can be measured. To answer such a question one should try find many SUSY particles and measure their decay patterns as accurately as possible. For example one finds that the production and decay of  $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$  provides good rates for a trilepton signature if the chargino and neutralino masses are below 200 GeV. The observation of such events should allow to measure accurately the dilepton mass distribution which is sensitive to the mass difference between the two neutralinos. Depending on the used MSUGRA parameters one finds that the  $\tilde{\chi}_2^0$  can have two or three body decays. The relative  $p_t$  spectra of the two leptons can be used to distinguish the two possibilities.

In contrast to the rate limitations of weakly produced SUSY particles at the

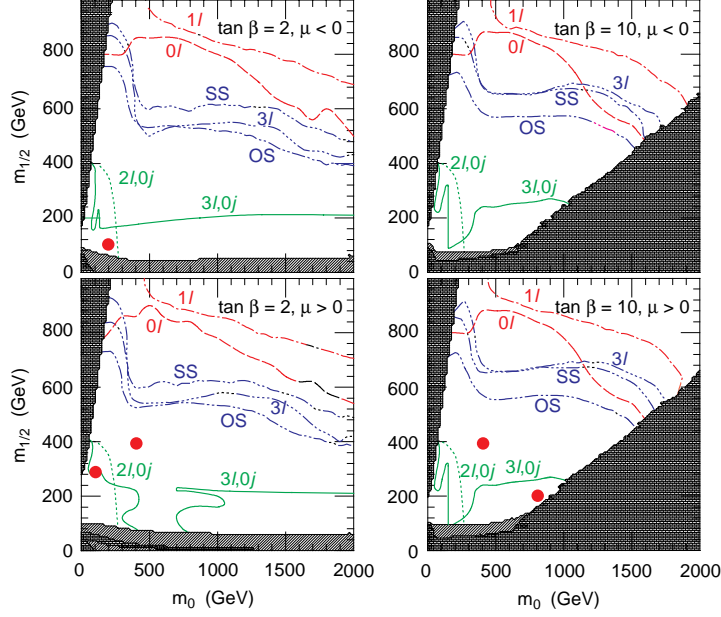


Figure 17: Expected sensitivity for various SUSY particles and signatures in the  $m_0 - m_{1/2}$  plane using an integrated luminosity of  $10 \text{ fb}^{-1}$  at the LHC [30]. The different curves indicate the expected sensitivity for SUSY events with  $n$  leptons ( $\ell$ ) and for events with lepton pairs with same charge (SS) and opposite charge (OS).

LHC, detailed studies of the clean squark and gluino events are expected to reveal much more information. One finds that the large rate for many distinct event channels allows to measure masses and mass ratios for several SUSY particles, which are possibly being produced in cascade decays of squarks and gluons. Many of these ideas have been discussed at a 1996 CERN Workshop [28]. Especially interesting appears to be the idea that the  $h^0$  might be produced and detected in the decay chain  $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h^0$  and  $h^0 \rightarrow b\bar{b}$ . The simulated mass distribution for  $b\bar{b}$  jets in events with large missing transverse energy is shown in Figure 18. Clear Higgs mass peaks above background are found for various choices of  $\tan \beta$  and  $m_0, m_{1/2}$ .



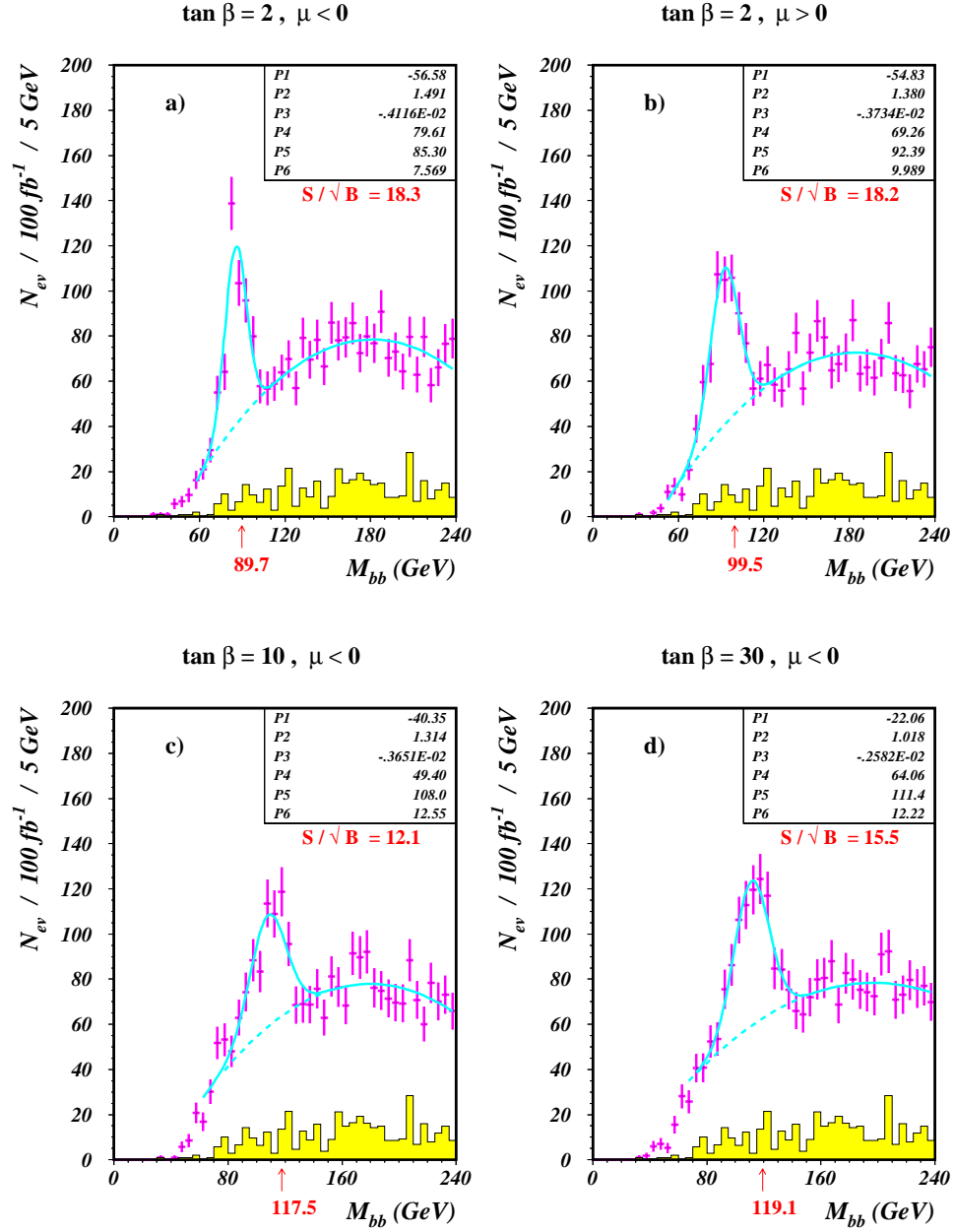


Figure 18: Possible inclusive Higgs signals in squark and gluino events, reconstructed from the invariant mass of  $h \rightarrow b\bar{b}$  with CMS and a luminosity of  $L=100 \text{ fb}^{-1}$  [31].

## 5 Summary

Searches for Supersymmetry at the highest energy particle colliders can be divided into the search for the MSSM Higgs sector and for the direct search for SUSY particles. So far no signs of neither a Higgs boson nor of any SUSY particles have been found.

The expected energy increase of the LEP II collider during the year 2000 might be just right to detect a Higgs boson up to a mass of about 105 GeV. In contrast, it appears that the LEP II experiments have reached almost the kinematical limit for the direct detection of supersymmetric particles as only marginal improvements, about 5%, can be expected from the future LEP II running.

The future high luminosity running of the TEVATRON might improve the existing sensitivity for SUSY particles by a factor of about 1.5–2 compared to today's mass limits. Consequently charginos might be seen up to masses of 200 GeV and squarks and gluinos up to masses of about 400 GeV. This reach should be compared with the expectations from the future LHC experiments. ATLAS and CMS studies indicate a good sensitivity up to masses of about 2 TeV. In addition, the detectable LHC squark and gluino cross sections, even for moderate masses well above any possible TEVATRON limit, are huge and LHC SUSY discoveries might be possible even with a luminosity of a few 100 pb<sup>-1</sup> only, obtainable almost immediately at the LHC switch on.

To finish this report on “Searches for Supersymmetry” we would like quote a few authorities:

*“Experiments within the next 5–10 years will enable us to decide whether Supersymmetry, as a solution to the naturalness problem of the weak interaction is a myth or reality”* H. P. Nilles 1984 [32]

*“One shouldn’t give up yet” .... “perhaps a correct statement is: it will always take 5-10 years to discover SUSY”* H. P. Nilles 1998 [33]

*“Superstring, Supersymmetry, Superstition”* Unknown

*“New truth of science begins as heresy, advances to orthodoxy and ends as superstition”* T. H. Huxley (1825–1895).

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